SUBGRADE SOIL EXHIBIT

of the

BUREAU OF PUBLIC ROADS

UNITED STATES DEPARTMENT *of* AGRICULTURE

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THIS exhibit illustrates the generally accepted practice in the new science of subgrade soils. Since scientific methods were first applied to these studies some 10 years ago, many phases of the subject have been explored. As was to be expected, some of the research has yielded negative results, but the bulk of the work has brought to light information of immense value to the highway engineer. It has taken time to weigh the contributions from the various investigations so that they might be assessed at their true value before being fitted into the general scheme of the new science. It is recognized that further research will amplify and extend our present knowledge. But to hasten the adoption of methods based upon the results already accomplished, there must come a general recognition of the value of the studies to the road builder. It is the purpose of this exhibit, therefore, to illustrate how the discoveries of investigators, both in this country and abroad, have been organized into a systematic and scientific method.

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The accomplishments of a decade of research are illustrated in the subgrade soil exhibit of the Bureau of Public Roads. Tests for determining the characteristics of the various types of soils; an exposition of the fundamental principles of soil physics and mechanics; a classification of soils into groups according to their relative value for subgrade purposes; methods of making a subgrade survey to determine the location of the different soils and the drainage conditions; and the method of designing road surfaces and cross-sections, based upon the data supplied by the subgrade survey, are illustrated on the 24 panels and demonstrated by the models and apparatus displayed upon the tables of the exhibit.

STUDIES OF SUBGRADE SOILS INITIATED IN 1920

Prior to 1920 it was generally recognized that clay soils were unsatisfactory for highway subgrades and that confined sand provided an excellent foundation. No information was available as to the relative values of various types of clays or as to soils ranging between the sands and the clays, although the Bureau of Public Roads in 1919 had begun the study of laboratory tests for determining the essential difference between various kinds of subgrade soils. In 1920, in connection with the study of the California State Highway System, made by the Bureau of Public Roads, the soil tests previously developed by the bureau were employed to determine the volumetric shrinkage of the soils under the road surfaces for which condition surveys were made. In making these soil-shrinkage studies, water was added until the various samples of soil mortar seemed to be of the same consistency. The idea of comparable amounts of water based upon the surface area of the soil grains in the mass had not been advanced.

During the same year—1920—the Bureau of Public Roads launched a nation-wide survey to determine the causes of failure of isolated sections of road surfacing. This work, carried on in cooperation with the State highway departments, and other research agencies, unearthed important discoveries within a short time.

In the Pacific Northwest, especially in the arid sections, where the subgrade shrank away and left the pavement without support in the dry season, it was believed that the change in volume of the subgrade soil was its most adverse characteristic. It was noted that the volume change was greatest for clays, less for silts, and negligible for sand. The volume change increased with a decrease in the size of the soil grain. To measure this volume change so that the

values for various soils should bear the proper relation, it was recognized that comparable amounts of water should be added based upon the total surface area of the grains in the soil mass.

To accomplish this the field moisture equivalent test was devised. With samples of soil wetted by this method, a lineal shrinkage test was made. It was found that wherever the value of the lineal shrinkage of the soil was less than 5 per cent, the soils were generally satisfactory for subgrade purposes, while soils with a value of more than 5 per cent were generally unsatisfactory.

With these tests available, a method of making a subgrade survey was developed by employing the soil maps published by the United States Bureau of Soils, locating the various types in relation to the survey for a new road, testing representative samples of each type, and making recommendations as to the design of surfaces based upon the known behavior of existing surfaces laid over similar soils in the vicinity.

In addition to the field tests developed in the Pacific Northwest, the laboratory of the Bureau at Arlington, Va., was examining with painstaking care other soil tests that looked promising. The Atterberg tests were found to be of particular value to the road builder.

BRIEF DESCRIPTION OF THE ATTERBERG TESTS

The Atterberg test process consists in the addition of water to the soil in conjunction with manipulation to determine two critical points. The liquid limit is the point where the soil passes from the liquid to the plastic state. With further manipulation the soil loses water and plasticity and begins to crumble when rolled in threads upon a glass plate. This point of conversion from the plastic to the solid state is known as the plastic limit. The values of the two limits are expressed in terms of the percentage of water present as compared with the dry weight of the soil. The difference between the percentages for the liquid and plastic limits is called the plasticity index. It is obvious that nonplastic soils, such as sands, do not possess either a plastic limit or a plasticity index.

According to the value of this index, Atterberg distinguishes between various soils as follows:

Friable soils.—Plasticity index less than 1.
Feebly plastic soils.—Index 1 to 7.
Medium plastic soils.—Index 7 to 15.
Highly plastic soils.—Index greater than 15.

In connection with the Atterberg tests the test for shrinkage limit is used. This is the point where the soil passes from the semisolid to the solid state. At this point there is no further decrease in volume with further loss of moisture by evaporation. The shrinkage limit is expressed as the percentage of moisture present as compared with the dry weight of the soil.

RELATIONSHIP BETWEEN TEST VALUES FOUND TO EXIST

While experimentation with the various tests was being carried on, it was found that a relationship existed between some of them and not between others. It was found that the Rose tests for field

moisture equivalent and lineal shrinkage, the Atterberg tests, and the test for the centrifuge moisture equivalent, all of which represented critical values when water was admixed with soil, could be used in combination so as to detect many of the important adverse and beneficial elements that affected a subgrade soil. It is probable also that these tests may serve to throw some light on such fundamental characteristics of the soil as the compressibility, elastic expansion, and permeability. In addition, the Bouyoucos hydrometer method was included where it was necessary to make a mechanical analysis because it could be performed with greater facility than the standard test. The master charts used to detect the character of subgrade soils based upon test values are shown on the panel illustrated in Figure 16.

SOIL CHARACTERISTICS IDENTIFIED BY THE VARIOUS TESTS

To give some idea of the manner of interpreting the results of these tests, a brief exposition of the characteristics of the soil as revealed by them follows:

Liquid limit.—This value indicates the minimum moisture content of the soil when in the liquid state. The liquid state is defined as the condition in which the shear resistance of the soil is so slight that a small force will cause it to flow. This test serves to distinguish soils with respect to the degree of lubrication necessary to permit them to slide. It may also disclose the relative roughness possessed by sand grains and the relative volume of the small-sized pores in other soils. Liquid limits of representative soil constituents tested in the laboratory have been as high as 40 for silts, 123 for mica flakes, 445 for peats, 138 for clays, 163 for diatoms, and 399 for colloids. Liquid limits from 20 to 40 are apt to indicate mixed materials with sand or silt predominating. Those considerably higher than 40 indicate the presence of mica, diatoms, organic matter, clay, or colloids.

Plastic limit.—This value indicates the minimum moisture content at which the soil can exist in the plastic state. Sand, mica, diatoms, and peat do not possess plasticity and, therefore, have no plastic limits. Silts occasionally, and clay and colloids always, possess plastic limits. Of certain representative subgrade soil constituents selected for study, silt had a plastic limit equal to 20, clay of 46, and colloids of 45.

Plasticity index.—This value indicates the extent to which a plastic soil may expand without becoming liquid. It measures the ability of soils to change shape without changing volume in an appreciable amount. It also indicates the cohesive properties of soils. Considered alone, the plasticity index serves only to distinguish cohesionless materials such as sand, mica, diatoms, and peat (plasticity index equal to zero) from soils possessiong cohesion such as clay and colloids.

Shrinkage limit.—This value is theoretically equal to the maximum moisture content of the soil when it has attained the minimum volume during the drying process. In general, for friable soils, the shrinkage limit may be anywhere between the liquid limit and 50

per cent of its value. For plastic soils, the shrinkage limit ranges between a water content of 10 and 20 per cent (in exceptional cases more), and no definite relation exists between the plastic and the shrinkage limit. In general, the lower the shrinkage limit the greater will be the possible volume change in a subgrade soil with variations in the moisture content.

Centrifuge moisture equivalent.—This value represents the percentage of water retained by the soil under a centrifugal force equal to one thousand times the force of gravity. Thus this test serves to distinguish soils which are permeable (sand, silt, mica, diatoms, peat, or flocculated clay, predominating), from those which are impermeable (clay and colloids predominating), when compressed by a centrifugal force equal to about 2 kilograms per square centimeter. It also assists in distinguishing permeable soils possessing capillarity in an amount sufficient to permit the occurrence of either frost heave or expansion, (silt, diatoms, mica, and peat), from those possessing capillarity in an amount sufficient to permit the occurrence of bulking only (sands).

Field moisture equivalent.—This value indicates the maximum amount of water a soil will absorb when its moisture content is gradually increased by adding water. The field moisture equivalent, the lineal shrinkage and the shrinkage limit are definitely related. Therefore the field moisture equivalent in combination with the lineal shrinkage may serve to disclose the shrinkage limit. (Fig. 16.) The field moisture equivalent test indicates the porosity possessed by sands and the degree to which moist compressed soils are apt to absorb water and expand. Thus, it indicates the degree of cohesion possessed by moist soils.

Field moisture equivalents when either approximately equal to or larger than the centrifuge moisture equivalents are apt to indicate soils possessing expansive materials (such as mica) in detrimental amounts. This fact furnishes a very important means of detecting silts with highly expansive properties.

Volumetric change.—The relation between volumetric change and lineal shrinkage is shown by the curves on the panel reproduced in Figure 16. The lineal shrinkage represents the percentage of reduction in length when a soil bar is dried after being wetted with an amount of water equal to the field moisture equivalent. A lineal shrinkage percentage of 5 has been suggested as the maximum value for a good soil mortar. When the lower liquid limit of colloidal soils exceeds 35, the volumetric change is apt to exceed 17, and the lineal shrinkage is likely to be greater than 5. In its relation to the field moisture equivalent the lineal shrinkage of a soil furnishes a means for estimating the shrinkage limit.

METHOD OF CLASSIFYING UNIFORM SUBGRADE SOILS

Using the master charts on the panel illustrated by Figure 16, uniform subgrade soils have been classified tentatively into 8 groups, which are described as follows:

Group A–1.—This soil consists of well-graded material from coarse to fine. It is highly stable under wheel loads regardless of moisture conditions. Florida sand-clay is representative of this group.

Identification.—By mechanical analysis the clay content varies from 5 to 10 per cent, the silt from 10 to 20 per cent, the fine sand from 23 to 27 per cent, and the coarse sand from 45 to 60 per cent. The effective size of the grains is approximately 0.01 millimeter, the uniformity coefficient is greater than 15, and the lineal shrinkage of the soil mortar is less than 5 per cent.

Group A–2.—This soil consists of graded material from coarse to fine. It is highly stable when fairly dry but apt to soften in wet weather. In extremely dry weather these soils become very dusty. South Carolina topsoil is representative of this group.

Identification.—By mechanical analysis the sand content should be not less than 55 per cent, the clay not less than 10 per cent, and the silt less than 10 or greater than 20 per cent. The lineal shrinkage of the soil mortar is greater than 5 per cent. The plasticity index of the soil mortar should be as shown on the master chart on the panel reproduced in Figure 16.

Group A–3.—This soil consists of coarse material only, with no binder. It has good drainage properties and is not heaved by frost. Florida sand is representative of this type.

Identification.—The liquid limit may be as low as 10 for beach sands offering but little frictional resistance to sliding and as high as 35 for crushed sands with a high resistance to sliding. The plasticity index is equal to zero; the centrifuge moisture equivalent is less than 12; and there is no significant shrinkage limit.

Group A–4.—These soils consist of silts without coarse material, and no appreciable clay content. They are apt to absorb water in quantities sufficient to cause a rapid loss in stability even without manipulation. They possess a high degree of capillarity and are heaved excessively by frost when wet. Minnesota silt is representative of this group.

Identification.—The liquid limit ranges from 20 to 40 and may reach 45. The plasticity index is less than the amount indicated by curve 3 on the master chart on the panel reproduced in Figure 16. The shrinkage limit does not ordinarily exceed 25 and it may reach 30. The centrifuge moisture equivalent is apt to be greater than 12 and to bear the relationship to the liquid limit indicated by curve 10. The expansive variety containing mica has a field moisture equivalent higher than the centrifuge moisture equivalent.

Group A–5.—This soil is similar to that of Group A–4 except that it provides highly elastic riding surfaces with appreciable rebound upon removal of load, even when dry. A micaceous sandy loam from Maryland is representative of this group.

Identification.—The liquid limit is generally greater than 20, and often greater than 35. The plasticity index is smaller than the amount indicated by curve 3. The shrinkage limit may be as small as 25 but it is generally greater than 30 or the amount indicated by curve 6. The field moisture equivalent is much larger than the amount indicated by curve 11. There is seldom water-logging in the centrifuge moisture equivalent test.

Group A–6.—These subgrades consist of clay soils without coarse material. In the wet compressed state they absorb water only if manipulated. Deformation occurs slowly and there is little rebound upon removal of the load. The soil possesses shrinkage

properties and may be unsatisfactory if used in fills because of excessive volume change. There is not apt to be adverse frost heave unless the soil is in an extremely permeable state. Missouri colloidal clay is typical of this group.

Identification.—The liquid limit is 35 or greater. The shrinkage limit approximates the amount represented by curve 5. There is water-logging when the centrifuge moisture equivalent exceeds 40. The field moisture equivalent is not apt to be appreciably larger than the amounts represented by curve 11.

Group A–7.—These soils are similar to those in Group A–6 except that when moist they are apt to deform quickly when loaded, and rebound in a manner similar to Group A–5 subgrades upon removal of load. A gumbo from the Red River Valley in Minnesota is representative of this group, as is also an expansive Missouri clay.

Identification.—The liquid limit is 35 or greater. The plasticity index lies between curves 3 and 4 on the master chart shown on the panel illustrated by Figure 16. The shrinkage limit may be equal to or greater than the amounts indicated by curve 5. The field moisture equivalent lies between curves 11 and 12.

Group A–8.—These soils consist of very soft peats and mucks. They are apt to contain capillary moisture in abnormally large amounts far above the ground-water level. A Minnesota muck that is apt to displace laterally under a superimposed fill is representative of this group.

Identification.—The liquid limit is 45 or greater. The plasticity index is less than the amount indicated by curve 3. The shrinkage limit approaches the values indicated by curve 6. The field moisture equivalent is greater than the amount represented by curve 11.

SUGGESTED TYPE OF SURFACING FOR THE VARIOUS SOIL GROUPS

The type of surface which has been generally found suitable for the various soil groups follows:

Group A–1.—This type of soil usually has sufficient stability to require only a wearing course. A surface treatment consisting of a prime coat followed by a surface application of bituminous material, covered with a blotting layer of crushed granular material, has been successfully used in Florida.

Group A–2.—After being stabilized by treatment, the same type of surface used in Group A–1 soils should be adequate. Where the soil is not treated, load distribution should be accomplished by moderately thick nonrigid surfaces or thin rigid pavements.

Group A–3.—If the soil is treated, a substantial wearing course should be adequate. On untreated soils moderately thick nonrigid or thin rigid pavements are desirable.

Group A–4.—When natural or artificial drainage is adequate a concrete pavement may be built of medium thickness (not less than 8 inches at the sides and 6 inches at the center), or a macadam surface may be built, either thick or moderately thick depending upon whether the soil is untreated or treated. When the groundwater level is high and drainage impracticable, macadam is an un-

suitable surface. In this case a thick concrete pavement should be used (not less than 9 inches at the sides and 7 inches at the center), with crack control and steel reinforcement.

Group A–5.—Macadam surfacing should be used on soils of this group only after the subgrade has been stabilized by both treatment and drainage. When the ground-water level is high and drainage is impracticable, a thick concrete pavement should be used (not less than 9 inches at the sides and 7 inches at the center), with crack control and steel reinforcement.

Group A–6.—When the soil is in a homogeneous state and drainage is not feasible, ample load distribution should be provided by a thick macadam surface or a rigid pavement. The required degree of load distribution depends upon the softness of the subgrade. Macadam should be used only after the soil has been surface-treated. In rigid pavements crack control is necessary to reduce the adverse effect of nonuniform subgrade shrinkage.

When the soil is in a permeable state and drainage is feasible, either macadam or rigid-type surfaces may be used; but when drainage is not feasible, very strong macadam should be used, or a rigid pavement with crack control and steel reinforcement.

Group A–7.—The proper types of surface are identical with those shown for Group A–6 subgrades for the condition where the soil is in a homogeneous state and drainage is not feasible.

Group A–8.—On soils of this group the pavement requires ample "beam" strength, adequate crack control, and steel reinforcement.

CLASSIFICATION OF NONUNIFORM SUBGRADE SOILS

Nonuniform subgrades are classified on the panel illustrated in Figure 23 into Groups B–1, B–2, and B–3. The classification is based upon the structure of the soils as it exists in the field instead of upon the character of the constituent soil material as in the uniform subgrades. Generally speaking the nonuniform subgrades lack stability and require heavy rigid surfaces. The detailed types of surface suggested are shown on the panel reproduced in Figure 24.

METHOD USED IN MAKING A SUBGRADE SURVEY

In conjunction with the routine tests and soil classification by groups which have been already described, a method of making a subgrade survey has been developed by the Bureau of Public Roads in collaboration with the Bureau of Chemistry and Soils of the United States Department of Agriculture. The process consists essentially in locating the various types of soils in relation to the survey stations, and describing the drainage conditions. The soil types are located by borings made along the center line and along the top or the toe of the side slopes. The information with regard to the various soil types and layers is plotted so as to form soil profiles. Representative samples of each of these layers are taken and tentatively classified. They are then placed in canvas bags properly marked and forwarded to the laboratory for final classification into Groups A–1, A–2, etc.

Data sheets for the designing engineer are then prepared upon which are plotted the soil profile and the drainage conditions, with recommendations as to the design of the surface and the proposed drainage system. The basic information is illustrated on the panel reproduced in Figure 14.

SUMMARY OF SUBGRADE SOIL EXHIBIT

The 24 panels in the exhibit, together with the accompanying table models (models not illustrated in Figures 1 to 24, inclusive), present a brief résumé of the present methods of classifying subgrade soils, making a subgrade survey, and designing road surfaces.

The panels illustrated by Figures 2 to 12, inclusive, illustrate research findings with regard to the physics and mechanics of soils included under the heads of voids ratio, moisture content, porosity, cohesion and friction, capillary moisture, expansion, shrinkage, permeability, frost action, compression, and elasticity.

The panels reproduced as Figures 1 and 14 outline the purpose of the subgrade survey and the method used.

Figures 15 and 16 illustrate panels that show the relationship between the various soil tests and the master charts used to classify uniform subgrade soils into the eight suggested groups.

Figures 17 to 22, inclusive, are reproductions of panels that identify the soils of the various groups, define the test limits that characterize them, and describe the type of surfacing that is recommended.

The panels illustrated by Figures 23 and 24 describe the structure of the nonuniform subgrades, suggest methods of treatment where applicable, and recommend types of surface.

Figure 13 is a reproduction of the panel that illustrates how the degree of uniformity of subgrade support affects the design of rigid pavements.

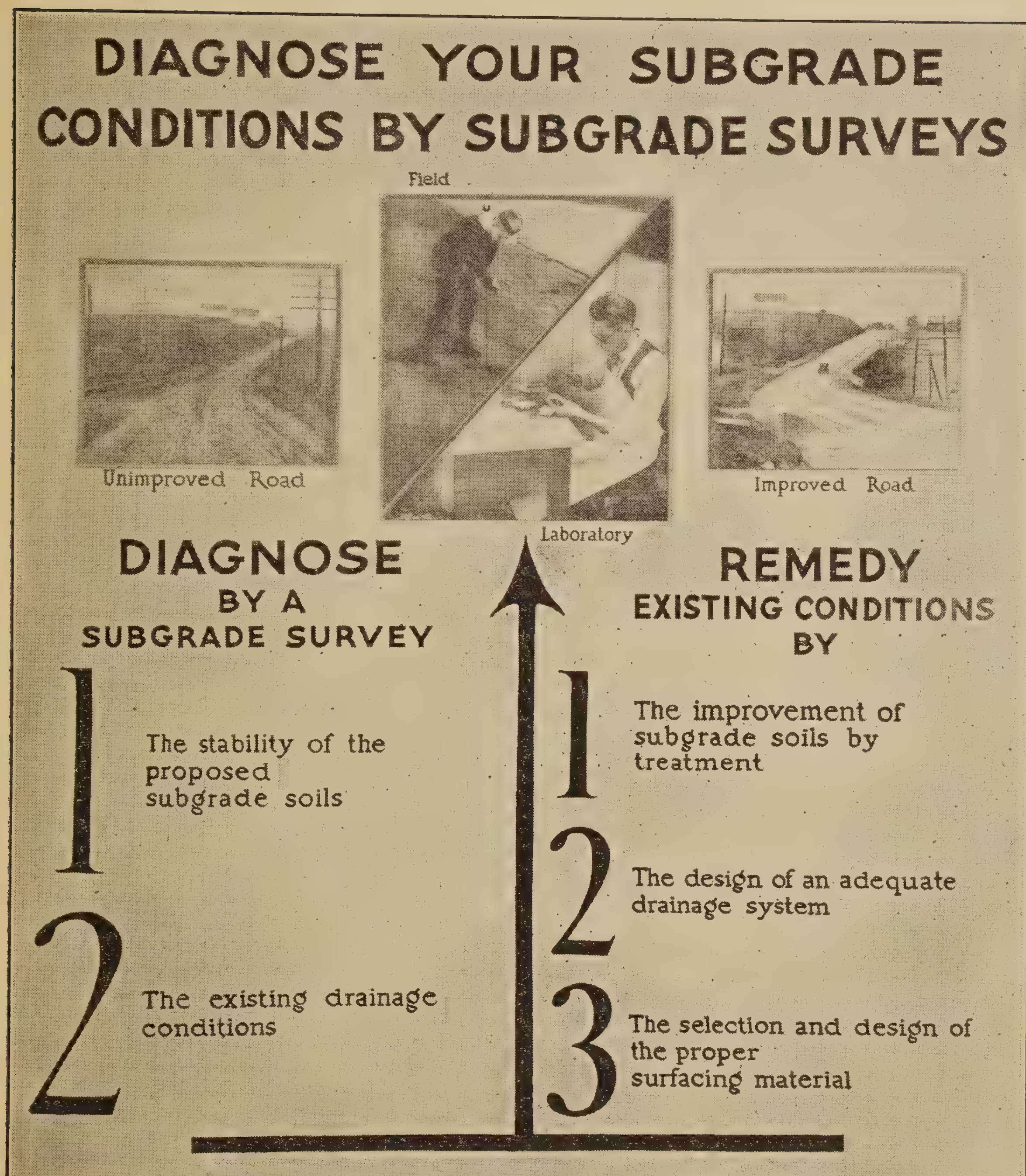
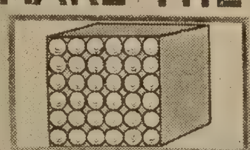


FIGURE 1.—Subgrade surveys

THE VOIDS RATIO DETERMINES THE DENSITY OF THE SUBGRADE SOIL, AND SOILS IN THEIR DENSEST STATE MAKE THE MOST SATISFACTORY SUBGRADES



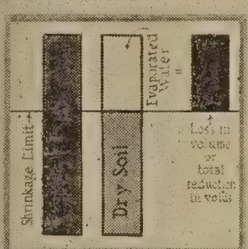
1 CUBIC-FOOT BOX
Containing 2-inch diameter spheres considered to represent soil particles.

DEFINITION.-The VOIDS RATIO is the ratio of the volume of voids to the volume of the soil particles in the soil mass.

LET e = Voids Ratio
V_v = Total Volume of voids in a soil mass.
V_s = Total Volume of soil particles in a soil mass.
THEN:— $e = \frac{V_v}{V_s}$ —— FORMULA No. 1

THE VOIDS RATIO e VARIES:

1.-With variation in degree of compaction, the number of soil particles remaining constant.
2.-With increase or decrease in moisture content, the number of soil particles remaining constant.
3.-With increase or decrease in total number of soil particles, the total volume of the soil mass remaining constant.



LET V = Volume of wet soil
V_o = Volume of dried soil
M_w = Weight of moisture content in grams in wet soil
M_{w_o} = Weight of moisture content in grams in dried soil
e_o = Voids Ratio of dried soil
M_v = Volume of moisture content in cubic centimeters in wet soil
M_{v_o} = Volume of moisture content in cubic centimeters in dried soil
C_o = Change in volume of soil in per cent
e = Voids Ratio of wet soil

THEN $C_o = \frac{e-e_o}{1-e_o} \times 100 = \frac{V-V_o}{V_o} \times 100 = \frac{M_w-M_{w_o}}{V_o} \times 100 = \frac{M_v-M_{v_o}}{V_o} \times 100$ FORMULA No. 2

The last two equations in Formula No. 2 are true only where M_{w_o} is above the shrinkage limit

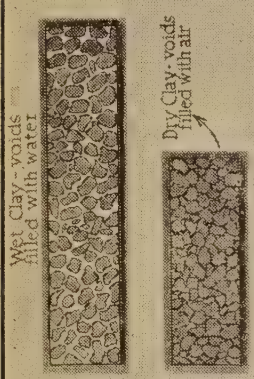
VOIDS RATIOS OF VARIOUS SOIL CONSTITUENTS WHEN AT THE YIELD POINT
(The yield point of the soil equals the minimum moisture content at which the deformations of the soil increase excessively without appreciable increase in load.)

TYPES OF SOIL	VOIDS RATIO AT YIELD POINT *	TYPES OF SOIL	VOIDS RATIO AT YIELD POINT
Sand	0.41	Organic Matter - Everglades Peat	1.50
Silt - Rock Creek Park, D.C.	0.53	Diatoms - Celite	2.39
Colloids - Bentonite	0.92	Mica Flakes - 20 to 100 mesh	2.58
Clay - Yaguajay	1.22		

* Yield point for plastic soils = L.P.L. (lower plastic limit)
Yield point for friable soils = 75 per cent of L.L.L. (lower liquid limit)

FIGURE 2.—Voids ratio

THE MOISTURE CONTENT OF A SOIL DETERMINES ITS SUITABILITY FOR SUBGRADE PURPOSES



DEFINITION.—MOISTURE CONTENT is equal to the weight of the water present expressed as a percentage of the dry weight of the soil

LET w = Moisture content in per cent of dry weight of soil in grams
w_v = Moisture content in per cent of dry volume of soil in cubic centimeters
W = Weight of wet soil in grams
W_o = Weight of dry soil in grams
V = Volume of wet soil in cubic centimeters
V_o = Volume of dry soil in cubic centimeters
M_w = Weight of moisture content of wet soil in grams
M_v = Volume of moisture content of wet soil in cubic centimeters
G = Specific gravity of soil particles
e = Voids ratio

Then by definition $w = \frac{M_w}{W_o} \times 100$ FORMULA No. 3

Substituting $M_w = W - W_o$ in Formula No. 3
Then $w = \frac{W - W_o}{W_o} \times 100$ FORMULA No. 4

Again since 1 cubic centimeter of water weighs 1 gram
Then $M_w = M_v$ FORMULA No. 5

Multiplying Formula 3 by G $wG = \frac{M_w G}{W_o} \times 100$
And since by definition $V_o = \frac{W_o}{G}$
Then $wG = \frac{M_w}{V_o} \times 100 = \frac{M_v}{V_o} \times 100 = w_v$ (by definition) FORMULA No. 6

Again substituting $e = \frac{M_v}{V_o} = \frac{M_w}{V_o}$ and $V_o = \frac{W_o}{G}$ in Formula 3
$w = \frac{e}{G} \times 100$ or $e = \frac{wG}{100}$ (true only above the shrinkage limit) FORMULA No. 7

Also substituting Formula 6 in Formula 7
Then $e = \frac{w_v}{100}$ (true only above the shrinkage limit) FORMULA No. 8

EXAMPLE.—Soil sample weighs 30 grams when wet and 25 grams when dry, and the soil particles have a specific gravity of 2.65
Then by Formula 4 $w = \frac{30-25}{25} \times 100 = 20$ per cent
And by Formula 6 $w_v = 20 \times 2.65 = 53$ per cent
And by Formula 8 $e = \frac{53}{100} = 0.53$

FIGURE 3.—Moisture content

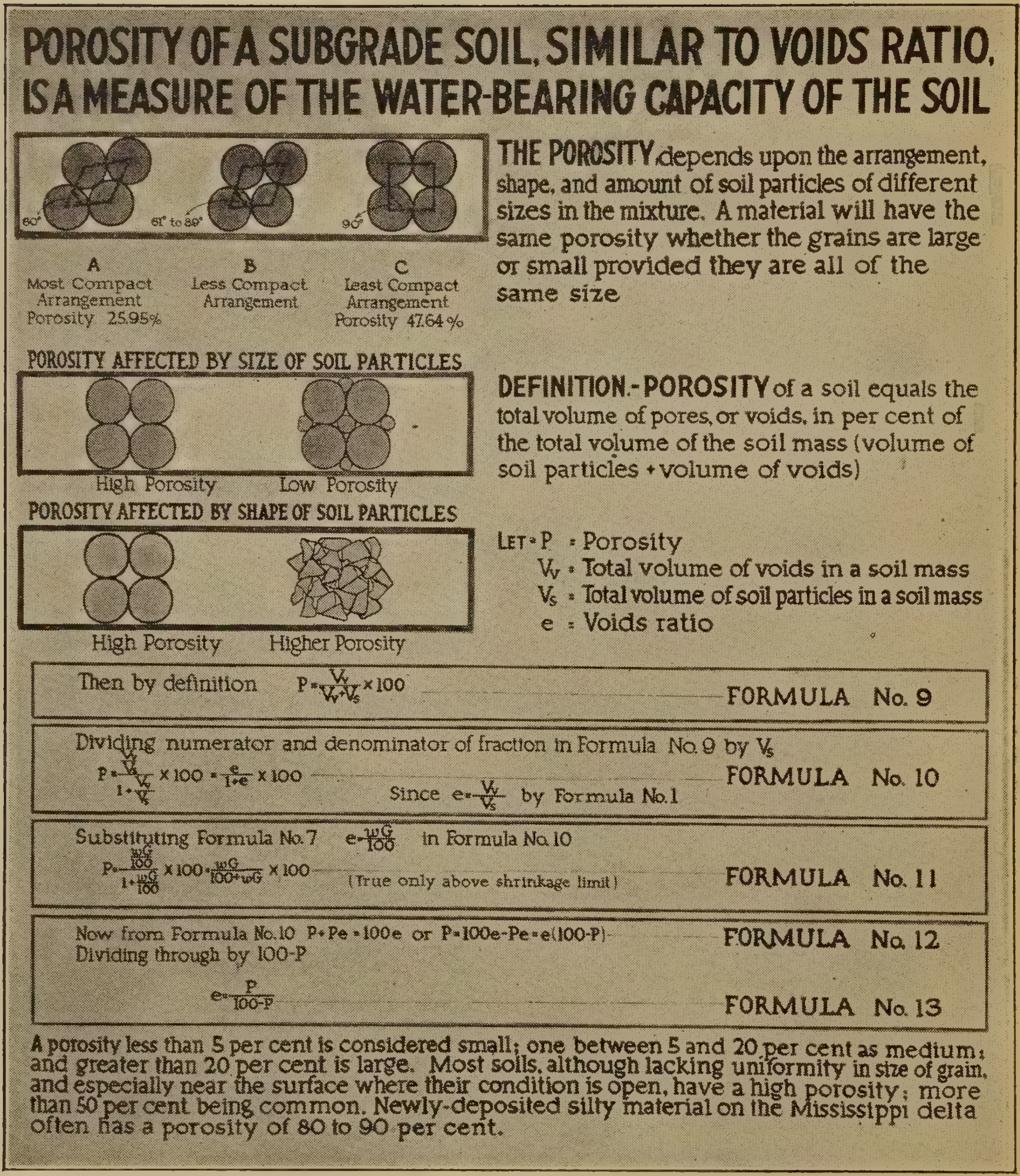


FIGURE 4.—Porosity

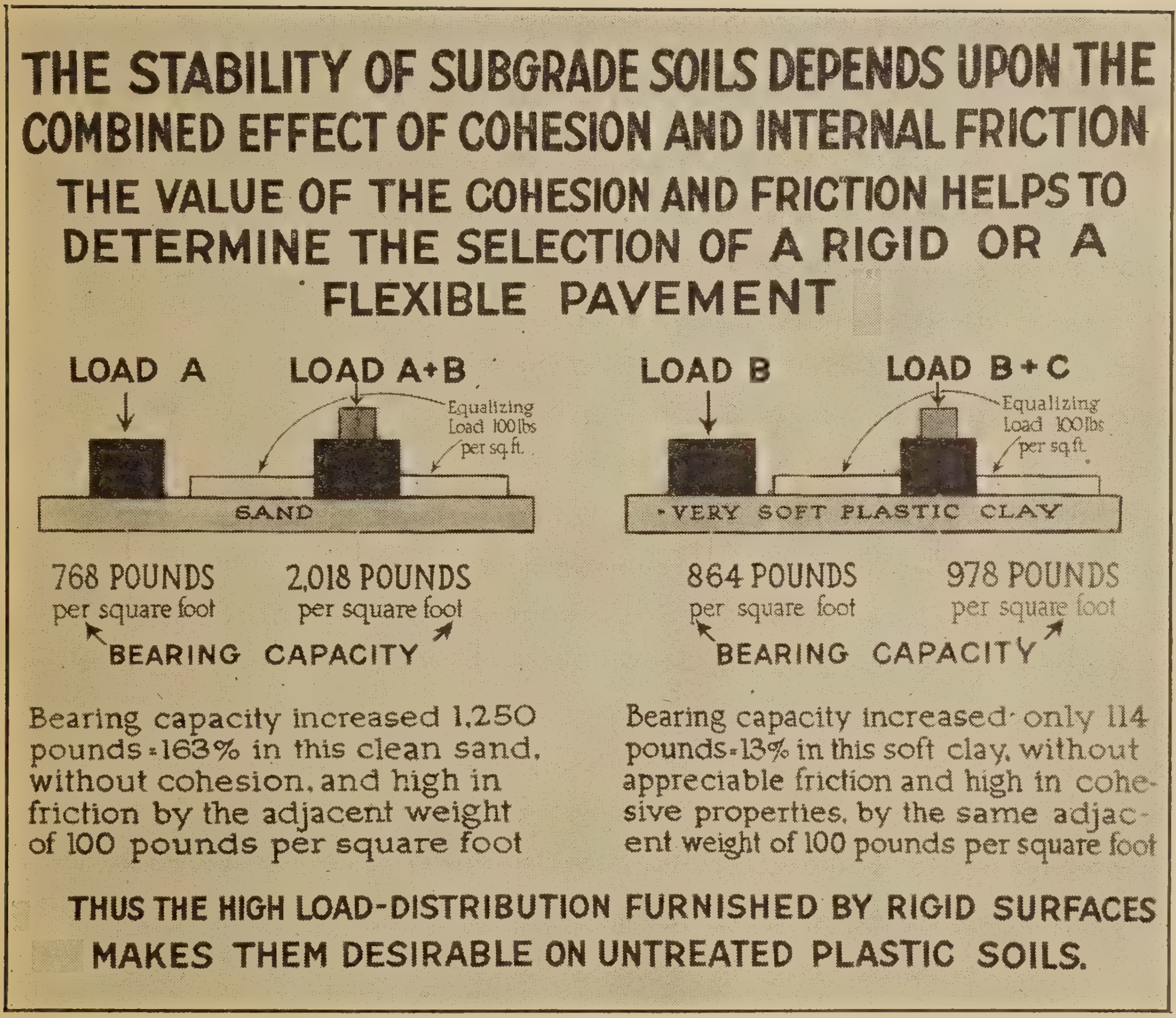
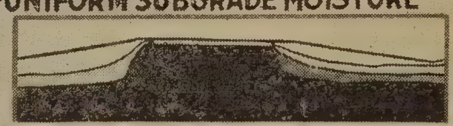


FIGURE 5.—Cohesion and friction

SHRINKAGE OF SUBGRADE SOILS IS CAUSED SOLELY BY CAPILLARY PRESSURE. IT MAY BE ELIMINATED BY MAINTAINING A CONSTANT MOISTURE CONTENT

EXAMPLES OF UNIFORM AND NON-UNIFORM SUBGRADE MOISTURE

No Shrinkage - Uniform Moisture Content in Subgrade



Apt to Shrink under Edge of Pavement Non-uniform Moisture Content in Subgrade

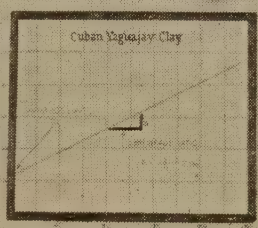
SHRINKAGE is the reduction in volume caused by the soil losing moisture. In the liquid state the capillary pressure that causes shrinkage is zero. As evaporation proceeds the capillary pressure increases until it equals the resistance of the soil particles to further reduction in volume. The moisture content at this state of equilibrium is called the 'shrinkage limit.' Further evaporation causes the surfaces of the capillary-water columns to retreat into the soil mass with no further reductions in the soil volume.

The voids ratio of representative soil constituents illustrates the possible shrinkage of each type

TABLE 1 - VOIDS RATIO OF REPRESENTATIVE SOIL CONSTITUENTS IN THE LIQUID AND DRY STATE

Constituents	Sand	Silt	Organic Matter	Clay	Diatoms	Mica	Colloids
Voids Ratio - Wet	0.54	0.71	2.00	2.65	3.19	3.44	8.18
Voids Ratio - Dry	0.50	0.50	0.65	0.29	2.62	4.48	0.12
Difference - Possible Shrinkage	+0.04	+0.21	+1.35	+2.36	-0.37	-1.04	+8.06

SOIL PATS



Volume change in per cent

When soils shrink the rate of volume change is proportional to the volume of water lost. The 'shrinkage ratio' is the per cent volume change for each per cent loss above the shrinkage limit.

LET S = Moisture Content at the shrinkage limit expressed as a percentage of the dry weight
R = Shrinkage Ratio
V = Volume of wet soil in cubic centimeters
V_o = Volume of dry soil in cubic centimeters. This equals the volume at the shrinkage limit.
W = Weight of wet soil in grams C = Change in volume of soil in per cent
W_o = Weight of dry soil in grams G = Specific Gravity of soil particles
w = Moisture Content of soil in per cent of dry weight of soil in grams

Then $V-V_o$, the total moisture loss at the shrinkage limit, is numerically equal to $w-S$
Weight of water evaporated between V and $V_o = wW_o - SW_o$
Since specific gravity of water equals 1, the volume in cubic centimeters equals the weight in grams or $wW_o - SW_o = V - V_o$ And $S = w - \frac{V-V_o}{W_o}$ FORMULA No. 15

$$\text{And } R = \frac{\frac{V-V_o}{V_o}}{\frac{V-V_o}{W_o}} \text{ or } R = \frac{W_o}{V_o}$$ FORMULA No. 16

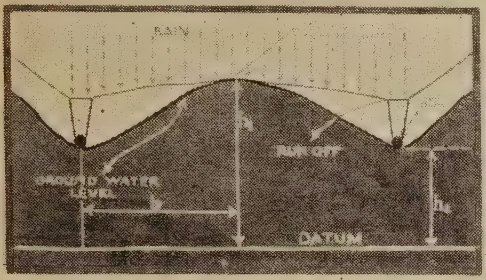
$$\text{And } G = \frac{W_o}{V_o - SW_o} = \frac{1}{\frac{V_o}{W_o} - S} = \frac{1}{\frac{1}{R} - S}$$ FORMULA No. 17

Finally the volume change may be computed for any variation in moisture content w_1 and w_2, when both w_1 and w_2 are above the shrinkage limit $C = (w_1 - w_2)R$ FORMULA No. 18

When only w_1 is above the shrinkage limit $C = (w_1 - S)R$ FORMULA No. 19
When both w_1 and w_2 are below the shrinkage limit $C = 0$

FIGURE 6.—Shrinkage

THE PERMEABILITY OF A SUBGRADE SOIL DETERMINES THE RATE AT WHICH IT PERMITS THE PERCOLATION OF WATER



The COEFFICIENT OF PERMEABILITY K indicates

1.-The proportionate amount of surface-water run-off

2.-The proportionate amount of water that percolates through the soil to the drains

DEFINITION:—COEFFICIENT OF PERMEABILITY equals the velocity in centimeters per second under a hydraulic gradient of 1.

LET h_1 = Ground-water elevation in centimeters above a given datum at a distance of b in centimeters from a drain

h_2 = Elevation of drain in centimeters above same datum

$\frac{h_1-h_2}{2b}$ = Average hydraulic gradient

V = Velocity of flow of water through soil in centimeters per second

A = Area of cross section of flow in square centimeters

Then $V = k\frac{h_1-h_2}{2b}$	FORMULA No. 20
And $Q = AV$	FORMULA No. 21

EXAMPLE.—LET h_1-h_2 = Depth of the drain = 4 feet = 122 centimeters

b = Distance from drain to center of earth road = 18 ft. = 550 centimeters

k = .02 For coarse sand

Q = Amount of water to be carried off by each cross drain

Then $V = .02\frac{122}{2{,}550} = .00222$ centimeters per second

If the distance between cross drains is 1,000 feet = 30,500 centimeters

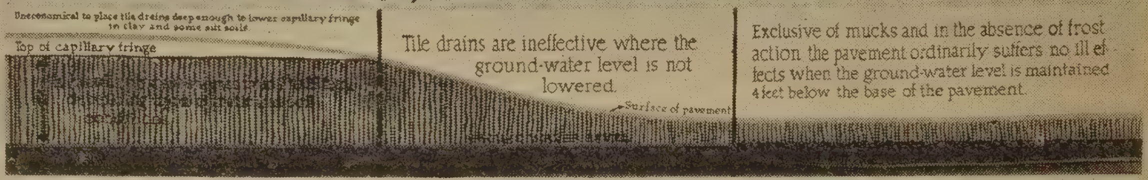
Then Q = 122×30,500×.00222 = 8,261 cubic centimeters per second

= 503 cubic inches per second = 0.29 cubic feet per second

k = .001	Q = 0.0146 cubic feet per second for fine sand
k = .00005	Q = 0.00073 cubic feet per second for diatoms
k = .0000002	Q = 0.000029 cubic feet per second for clay

FIGURE 7.—Permeability

ADVERSE EFFECT OF CAPILLARY MOISTURE IN SUBGRADE SOILS MAY BE REDUCED BY DRAINAGE, ONLY IF THE GROUND-WATER LEVEL IS LOWERED

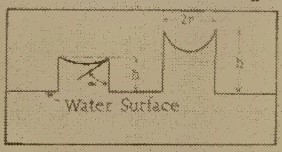


The variation in the ratio of the amount of gravitational to capillary water in soils of different character is shown in Table I.

TABLE I. EQUIVALENT THICKNESSES OF SOIL AND MOISTURE IN A 4-FOOT DEPTH OF THE WATER-AND-SOIL MIXTURES

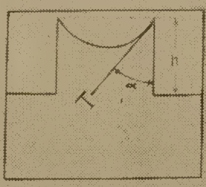
Soil Type	Thickness of Dry Soil	Thickness of Water			Total Thickness of Mixture of Soil and Water
		Total	Capillary-Not Removable by Drainage	Gravitational-Removable by Drainage	
	INCHES	INCHES	INCHES	INCHES	INCHES
Sand	23	25	7	18	48
Silt-Loam	23	25	13	12	48
Clay	20	28	21	7	48
Muck	9	39	29	10	48

DEFINITION.—CAPILLARITY is the ability of a soil to transmit moisture in a finely-divided state, in all directions, independent of both the direction in which gravity acts and the force of gravity



Capillary Tubes

LET $2r$ = Diameter of capillary tube in centimeters
T = Surface tension in dynes (per centimeter)
α = Angle of contact between the liquid and walls of the tube
h = Capillary rise in centimeters
ϱ = Density of the liquid
g = Gravity in dynes (per centimeter cubed)



Then the upward pull of the liquid in the tube because of capillarity = $T\cos\alpha\, 2r\pi$ (A)
And the downward pull equals the weight of the cylinder of the liquid = mass x gravity = $\pi r^2 h \varrho g$ —————— (B)
These two forces are in equilibrium when the top of the capillary column has reached its maximum height. At that point $T = 75.0$ approximately

α = Nearly 0°
$\cos\alpha$ = About 1
ϱ = About 1
g = 980

Equating Formulas (A) and (B) $T\cos\alpha\, 2r\pi = \pi r^2 h \varrho g$ and solving for h

$$h = \frac{2T\cos\alpha}{r\varrho g} = \frac{0.153}{r}$$

FORMULA No. 14

The capillary rise varies **INVERSELY** as the radius of the tube

CONTROL OF CAPILLARY MOISTURE:

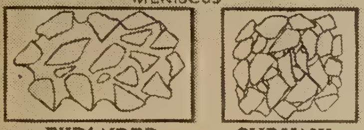
1: Since capillary water cannot rise without displacing air from the voids of the soil above, it follows that a subgrade seal of bituminous material should be effective for retarding the capillary rise of moisture.

2: Sprinkling the subgrade with water immediately prior to the application of the oil, opens the soil pores and permits the oil to enter the soil pores and follow the water to a greater depth than if no water had been applied.

FIGURE 8.—Capillary moisture

EXPANSION OF SUBGRADE SOILS CAUSED BY VARIATIONS IN MOISTURE CONTENT SHOULD BE CONTROLLED IF POSSIBLE

MENISCUS



EXPANDED - voids completely filled with water

SHRUNK - voids filled with water and air

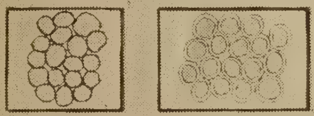
EXPANSION is the increase in volume caused by the penetration of water acting under capillary pressure. With further additions of water, the capillary pressure reaches equilibrium with the cohesive properties of the soil particles, the expansion stops, the soil particles are apt to change their relative position, and the soil may be transformed into the liquid state and flow.

TABLE.1-VOIDS RATIO OF REPRESENTATIVE SUBGRADE SOILS AT THE LIQUID STATE

Constituents	Sand	Silt	Organic Matter	Clay	Diatoms	Mica	Colloids
Voids Ratio	0.54	0.71	2.00	2.65	3.19	3.44	8.18

The "EXPANSIVE" soils are clay, colloids, and mica which possess cohesion and capillarity in appreciable amounts. The "INERT" or non-expansive materials are represented by sand which with the addition of only small amounts of water and manipulation may "BULK" instead of expanding.

DRY SAND "BULKED" SAND



VOIDS FILLED WITH WATER

"**BULKING**", with moderate additions of water, is caused by the surface films of water, around the grains, pushing the grains apart and expanding the sand. Further additions of water so as to fill the voids, reduce the surface tension to zero and cause a rearrangement of the soil grains so that the final wet volume may be less than the original dry volume.

DRY soils expand more than **WET** soils with further additions of water

TABLE 2.-EXPANSION OF SOIL CONSTITUENTS CAUSED BY WATER ABSORPTION IN PER CENT OF THE VOLUME OF THE COMPRESSED SAMPLES

Constituents	Sand	Silt	Organic Matter	Clay	Diatoms	Mica	Colloids
	PER CENT	PER CENT	PER CENT	PER CENT	PER CENT	PER CENT	PER CENT
Expansion — Dry	1.6	5.1	21.0	15.0	4.9	283.5	69.2
Expansion — Wet	1.4	4.1	6.2	7.8	4.5	44.2	73.0
Difference	+0.2	+ 1.0	+ 14.8	+ 7.2	+ 0.4	+ 239.3	− 3.8

The great expansive influence exerted by the surface films of water is made possible by the vast area of interstitial space in fine-grained sands

TABLE 3.-AGGREGATE SURFACE AREA=INTERSTITIAL-SPACE AREA COMPUTED FOR 1 CUBIC FOOT OF SOIL OF VARIOUS GRAIN SIZES

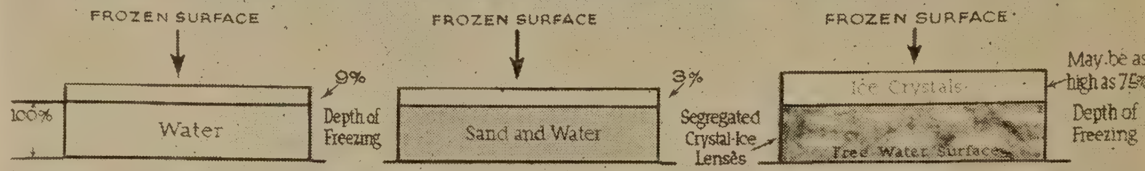
Kind of Soil	Average Diameter of Soil Spheres	Total Surface-Area of Soil Particles = Total Interstitial-Surface		Ratio of Diameters Sand=1	Ratio of Total Surface-Area Sand=1.
	MILLIMETERS	SQUARE FEET	ACRES		
SAND	1.00	1,000	1/43	1:1	1:1
FINE SAND	.02	50,000	1	1:50	50:1
CLAY	.001	1,000,000	20	1:1000	1,000:1

THE ABILITY OF SOILS TO EXPAND DEPENDS UPON:

1.- The size, shape, and character of the soil grains.
2.- Whether the original state of the soil is wet or dry, and the total variation in moisture content.
3.- Whether the soil contains cohesive clay in sufficient amounts to prevent disintegration.
4.- Whether some other cohesive element is present such as bituminous material that will resist water absorption and corresponding expansion.
5.- Whether in soils possessing capillarity the soil has compacted thoroughly in a damp condition so as to reduce the total possible amount of expansion.

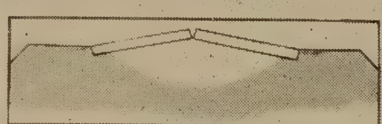
Figure 9.—Expansion

THE DESTRUCTIVE ACTION OF FROST IS CAUSED PRINCIPALLY BY THE SEGREGATION AND GROWTH OF ICE CRYSTALS



Pure water or sand with the voids filled with water increases when frozen only an amount equal to the greater volume of the solid ice.

But the same amount of clay with voids filled with water may swell 75 per cent because of the formation and segregation of ice crystals.



THE FORMATION OF ICE CRYSTALS PRODUCTIVE OF HEAVING OF ROAD SURFACES IS CAUSED BY:

1.-The ability of water, in soil pores larger than capillary dimensions at 0°Centigrade or slightly less (-1° to -4° Centigrade), to freeze

2.-The ability of water in soil pores of capillary size to resist freezing at abnormally low temperatures (as much as -70° Centigrade)

3.-The ability of freezable water in larger than capillary pores during the freezing, to draw upon the non-freezable water in capillary pores as a reservoir so as to increase the size of the ice crystals, as long as unfrozen water remains in the fine soil-pores.

THE AMOUNT OF HEAVING IN SOILS POSSESSING CAPILLARY PROPERTIES DEPENDS IN ADDITION TO TEMPERATURE UPON:

1.-The moisture content of the soil when freezing occurs.

2.-The relative number of freezable and non-freezable water particles existing in the soil.

3.-The speed with which non-freezable water drawn from adjacent capillary pores is replaced by capillary rise from a water table or seepage.

MEASURES THAT HAVE BEEN SUGGESTED TO PREVENT HEAVING ARE:

1.-Construct clay and silt subgrades as high above ground-water level as practicable.

2.-In silt and permeable clay subgrades use lateral subdrains to drain sags in grade, and to furnish outlets for water liberated during thaws under the center of the road, into the unfrozen under soil. This method eliminates "frost boils."

3.-Substitute, to the depth of frost penetration, material in which no excessive ice segregation develops.

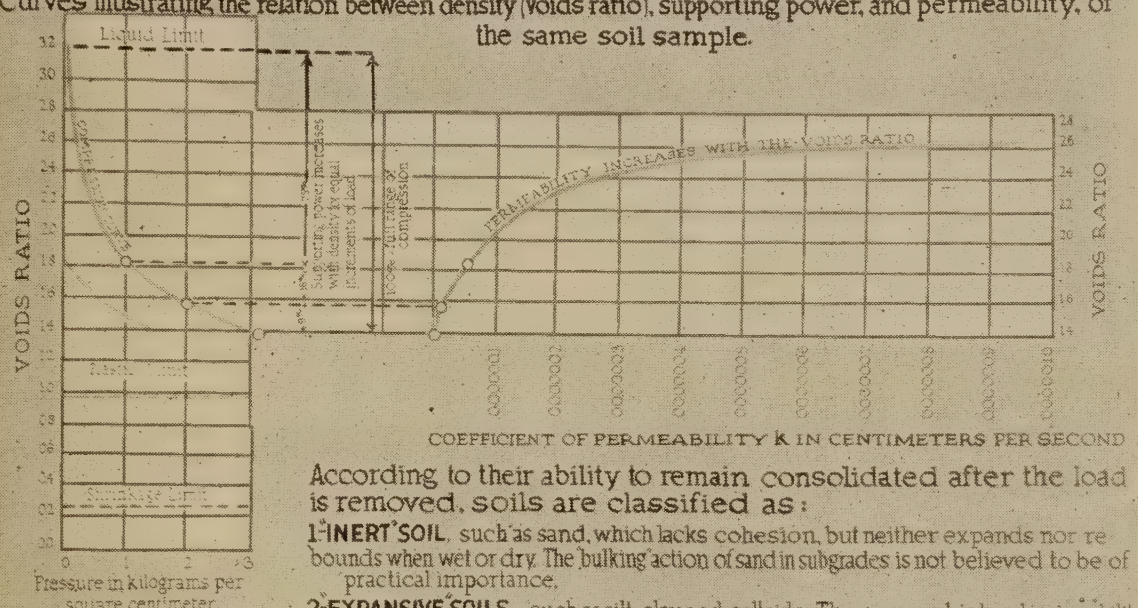
4.-Treat the subgrade with some appropriate material so as to reduce the freezing temperature.

5.-Prior to the construction of rigid pavements, construct insulating layers designed to reduce the depth of frost penetration.

FIGURE 10.—Frost action

COMPRESSION OF A SUBGRADE SOIL DIMINISHES ITS PERMEABILITY BUT INCREASES ITS DENSITY AND CONSEQUENTLY ITS SUPPORTING POWER

Curves illustrating the relation between density (voids ratio), supporting power, and permeability, of the same soil sample.



According to their ability to remain consolidated after the load is removed, soils are classified as:

1-"INERT" SOIL, such as sand, which lacks cohesion, but neither expands nor rebounds when wet or dry. The "bulking" action of sand in subgrades is not believed to be of practical importance.

2-"EXPANSIVE" SOILS, such as silt, clay, and colloids. They possess high cohesive ability and remain compacted when dry, but expand when water is added because the capillary pressure in the numerous capillary pores overcomes the cohesive force.

3-"ELASTIC" SOILS, such as mica, which rebound with the removal of load because of the effect of the scale-like particles; the rebound being greater when wet than when dry. (Therefore, clay or colloidal soils deposited in a wet condition can not be consolidated by a road roller. Thus soils of this type are unfitted for use in hydraulic fills, and jetting is of doubtful value).

(Supporting power varies with different soils, but all possessing moisture contents less than their yield point will support maximum allowable loads indefinitely without any increase in load).

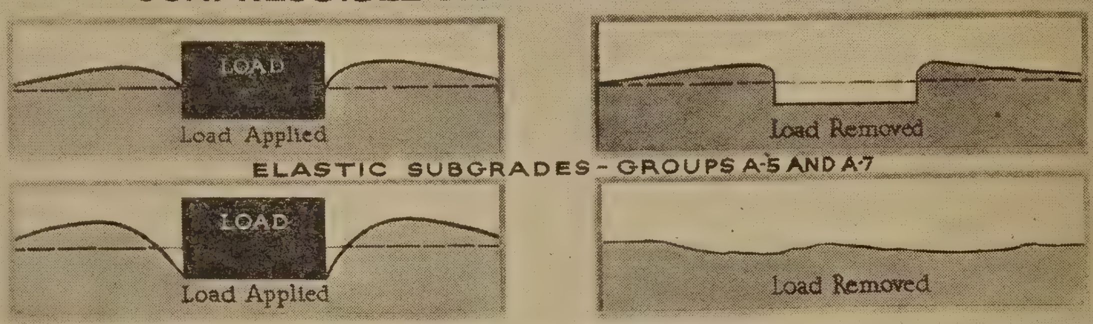
TABLE 1.- Computed supporting power of various subgrade soils depending upon counter-balancing weight of the paved surface called Q_1 (in pounds per square foot). These values are relative and not absolute.

SOIL	SUPPORTING VALUE IN POUNDS PER SQUARE FEET $Q_1=0$	$Q_1=100$
CLAY, Almost Liquid	400	500
CLAY, Very Soft	864	978
CLAY, Soft	1,857	1,991
CLAY, Fairly Stiff	4,982	5,134
CLAY, Stiff	8,050	8,225
CLAY, Very Stiff	12,528	12,760
SILTS, Wet	43	245
SANDS, Dry	768	2,018
SAND Predominating with some clay	6,035	6,935
SAND-GRAVEL MIXTURES, Cemented	17,838	19,080

FIGURE 11.—Compression

AS THE ELASTICITY OF SOILS INCREASES, THEIR STABILITY FOR SUBGRADE PURPOSES DIMINISHES

COMPRESSIBLE SUBGRADES-GROUPS A-4 AND A-6



EFFECT OF APPLYING AND REMOVING LOAD ON COMPRESSIBLE AND ELASTIC SUBGRADES

ELASTICITY is the ability of soils to rebound when the load is removed. It is caused by those soil constituents possessing abnormally high porosity when dry. These expand appreciably upon the removal of the load, without change in moisture content. Mica flakes, diatoms, and organic matter represent constituents of this character.

ADVERSE EFFECTS FROM ELASTIC SUBGRADES MAY DEVELOP AS FOLLOWS:

1.-An elastic subgrade, possessing cohesion, is apt to retain a certain degree of compaction after thorough rolling. A slight wetting by freshly-laid concrete, especially when the soil possesses expansive properties also, may cause a non-uniform rebound of the subgrade. This combined with absorption of water from the pavement may cause excessive cracking during the setting period.

2.-Movements of heavy material-trucks and mixing apparatus on the subgrade may produce distortions in the adjacent subgrade under the freshly-laid concrete so as to produce microscopic cracks in the pavement that are not visible for some time.

3.-Elasticity of the soil may prevent macadam surfaces from being bonded adequately during construction, or from retaining their bond subsequently. Under these conditions "alligator-hide cracks" are apt to develop. These cracks permit water to penetrate through the pavement, soften the subgrade, and cause failure.

CORRECTIVE TREATMENTS SUGGESTED FOR ELASTIC SUBGRADES:

1.-Stabilize the soil by the stage-construction method, prior to the construction of a high-type surface.

2.-Admix cohesive material (clay) where the absence of cohesion in the subgrade (highly-micaceous sands, etc.) interferes with the construction of the pavement.

3.-Make the subgrade as uniformly dense and moist as possible by breaking down all clods with a light-weight roller (about 3 tons), harrowing, and possibly sprinkling.

4.-Prevent, if possible, excessive moisture changes in the soil during the setting period of the concrete surface by the application of tar paper, bituminous coatings, or similar materials.

FIGURE 12.—Elasticity

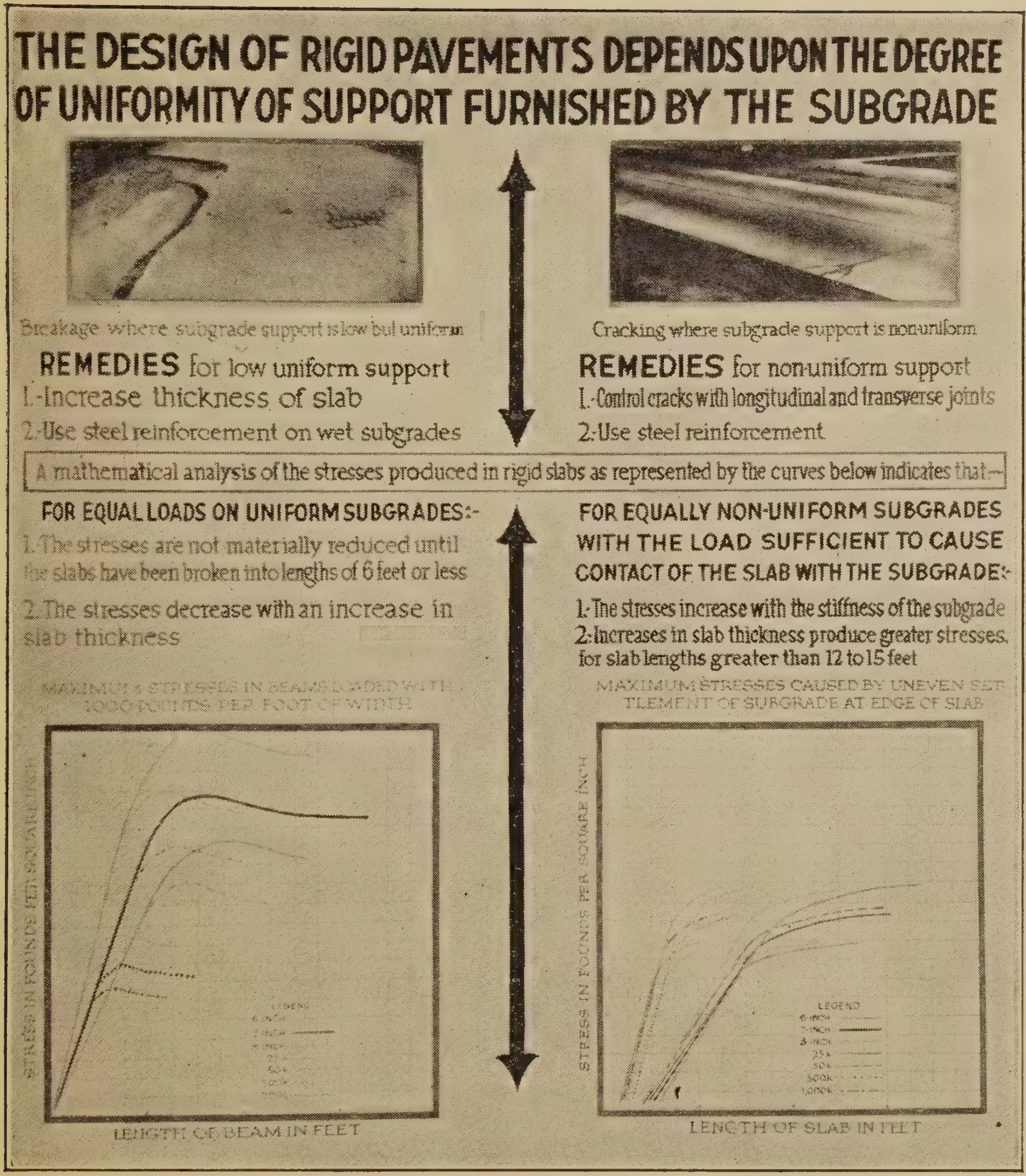


FIGURE 13.—Rigid pavement design

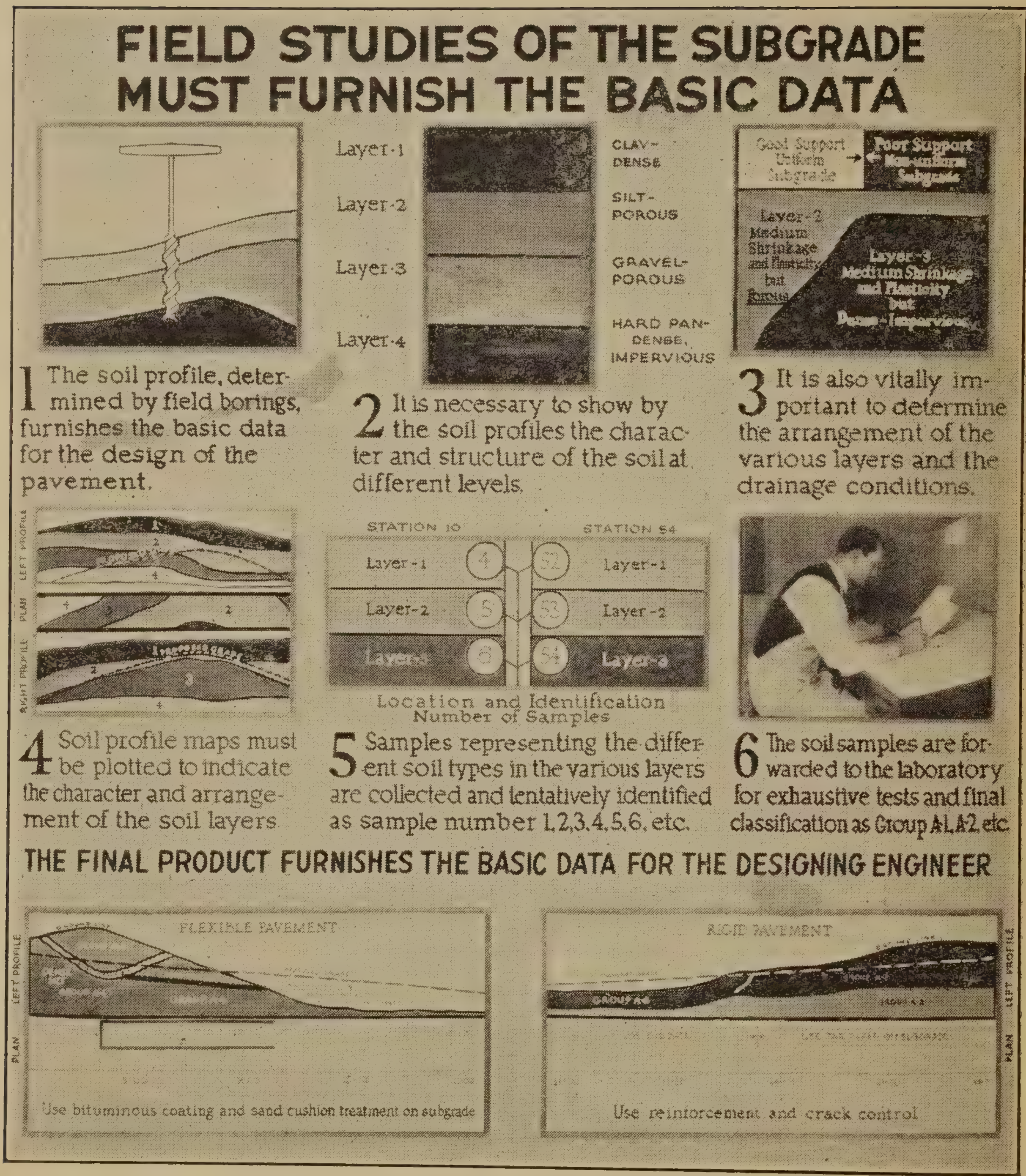


FIGURE 14.—Field studies

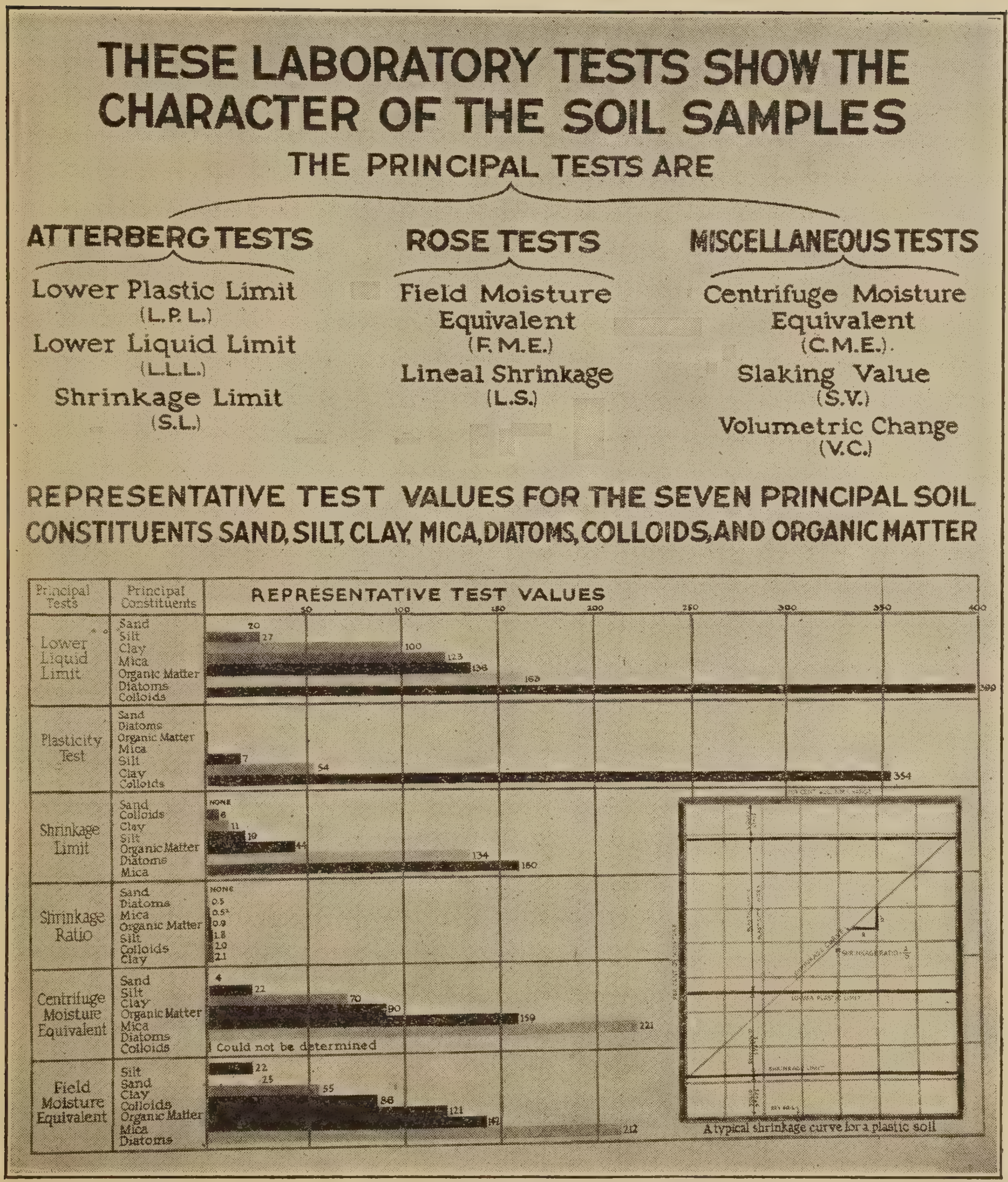


FIGURE 15.—Laboratory tests

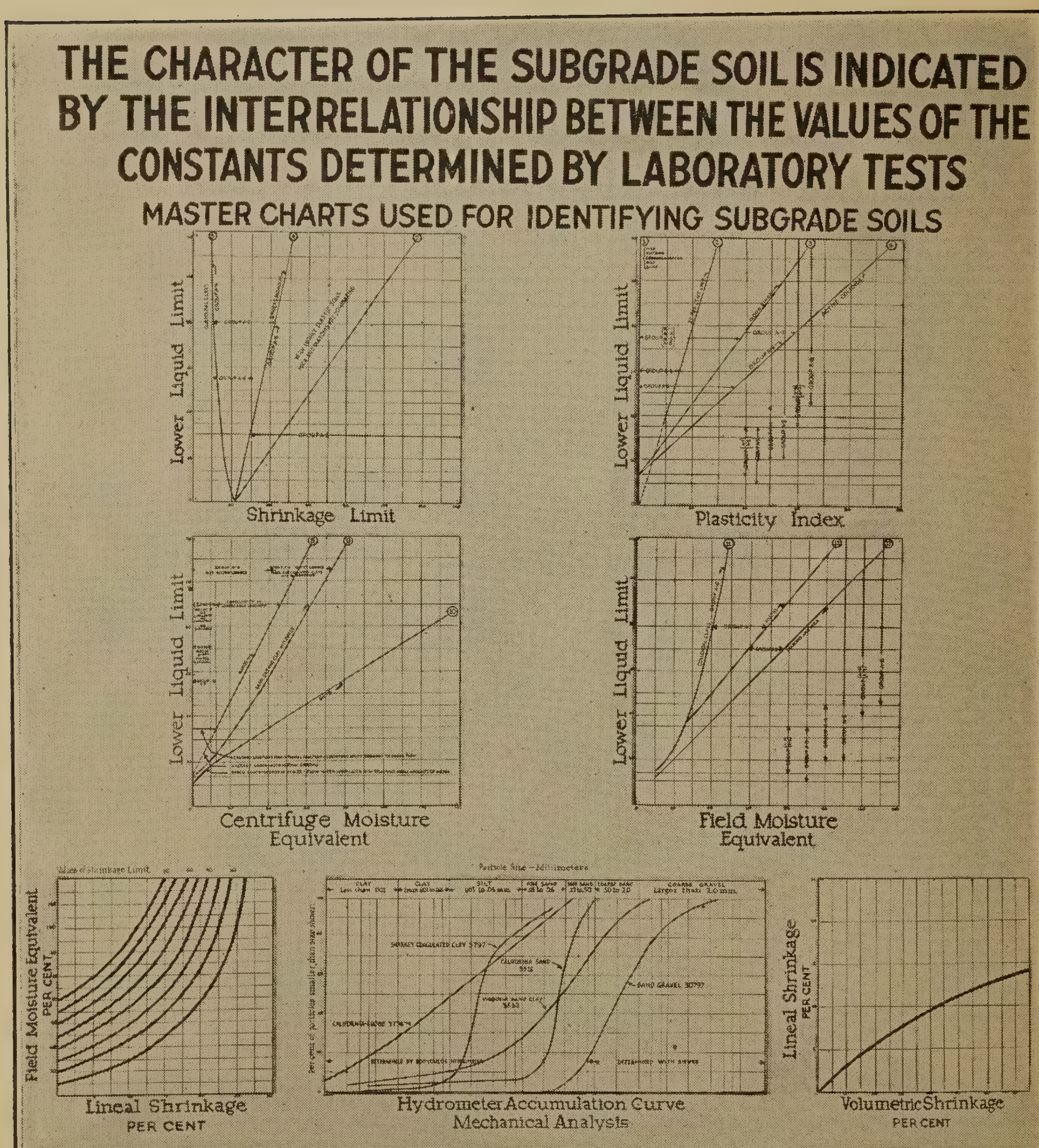


FIGURE 16.—Soil identification

SUGGESTED DESIGN OF GROUP A-1 SUBGRADES

CHARACTER OF SOIL.—Well-graded soil-mixture from coarse to fine material. It is highly stable under wheel loads irrespective of moisture conditions.

PREPARATION OF THE SUBGRADE.—This soil should be thoroughly puddled and then compacted with a multiple-ring or sheep's-foot roller. Drainage should be provided to maintain the ground-water level below the elevation where frost heave may occur.

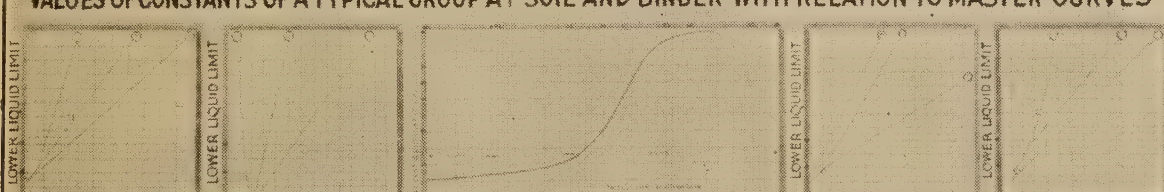
TYPE OF SURFACE PERMISSIBLE.—This type of soil usually has sufficient stability so as to require only a wearing course. A surface treatment consisting of a prime coat followed by a surface application of bituminous material, covered with a blotting layer of crushed granular material has been successfully used in Florida.

IDENTIFICATION of the soil is indicated by values shown in the following tabulation:

MECHANICAL ANALYSIS				Effective Size	Uniformity Coefficient	Lineal Shrinkage of Soil Mortar
Clay	Silt	Fine Sand	Coarse Sand			
PER CENT	PER CENT	PER CENT	PER CENT	MILLIMETERS		PER CENT
5 to 10	10 to 20	23 to 27	45 to 60	.01	15 and over	Less than 5

1.- Effective size is the diameter of grain than which 10 per cent of the soil particles are smaller and 90 per cent are larger
2.-Uniformity coefficient is the ratio of the size of grain than which there are 60 per cent of the sample finer, to the size than which there are 10 per cent finer.

VALUES OF CONSTANTS OF A TYPICAL GROUP A-1 SOIL AND BINDER WITH RELATION TO MASTER CURVES



O-Typical GROUP A-1 subgrade soil from South Carolina
□-Kaolin-not a member of this group-is ideal as a binder for GROUP A-1 SOIL

FIGURE 17.—Group A-1

SUGGESTED DESIGN ON GROUP A-2 SUBGRADES

CHARACTER OF SOIL:—A graded material from coarse to fine. The grading is either poor or the binder is inferior. It is highly stable when fairly dry but apt to soften in wet weather.

PREPARATION OF SUBGRADE.—Thorough puddling and compaction required similar to Group A-1 subgrades. Drainage needed, where ground water is high, to prevent frost heave and softening of the binder from below.

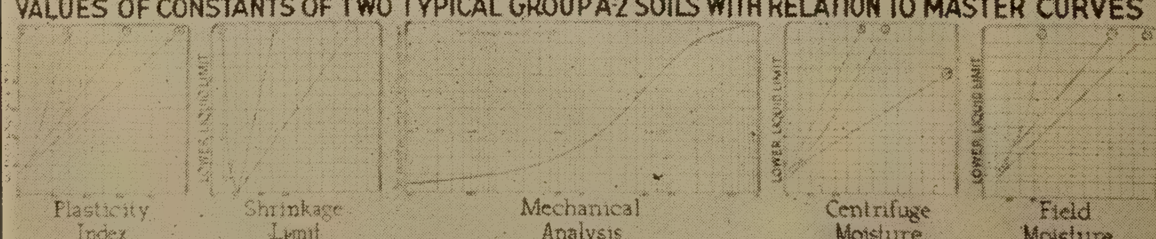
TREATMENT OF SUBGRADE: If the soil is deficient in coarse material, and has some plasticity, but low shrinkage properties (silty clays), an admixture of coarse granular material such as sand, gravel, slag, or crushed stone, will be beneficial. If the soil contains an abundance of coarse material and lacks clay and silt, or if the grading is proper but the plasticity and shrinkage are low, cohesive materials must be added. If the soil mortar has high shrinkage properties, add materials such as hydrated lime, and diatoms, that increase the porosity of the soil; or bituminous materials or Portland cement that reduce the moisture capacity of the soil.

TYPE OF SURFACE PERMISSIBLE:—After being stabilized by treatment, the same type of surface used on Group A-1 soils should be adequate, where the soil is not treated. Load distribution should be accomplished by moderately thick non-rigid surfaces or thin rigid pavements.

IDENTIFICATION OF THE SOIL INDICATED BY THE VALUES SHOWN IN THE FOLLOWING TABULATION:

MECHANICAL ANALYSIS			
Clay	Silt	Total Sand	Lineal Shrinkage of Soil Mortar
PER CENT	PER CENT	PER CENT	PER CENT
10 and Over	10 and Less or 20 and Over	55 and Over	5 and Over

VALUES OF CONSTANTS OF TWO TYPICAL GROUP A-2 SOILS WITH RELATION TO MASTER CURVES



○- A soil performing satisfactorily in a fill in Escambia Bay, Florida.
□- A satisfactory material for a topsoil surface in South Carolina.

FIGURE 18.—Group A-2

SUGGESTED DESIGN OF GROUP A3 AND A-4 SUBGRADES

CHARACTER OF SOIL-GROUP A-3:- This soil consists of coarse materials without any binder. The natural drainage is good and danger from frost heave is remote.

GROUP A-4:- These soils consist of silts without coarse material, and no appreciable clay content. They are apt to absorb water in quantities sufficient to cause rapid loss in stability even without manipulation. They possess a high degree of capillarity and are heaved excessively by frost when wet.

PREPARATION OF SUBGRADE-GROUP A-3:- This soil should be drenched with water and compacted with a light-weight roller.

GROUP A-4.- This subgrade should be sprinkled moderately and thoroughly consolidated with a heavy roller. Drainage should be provided that will intercept seepage and reduce the adverse effect of frost heave.

TREATMENT OF SUBGRADE-GROUP A-3:- An admixture of binder, or admixtures of bituminous materials will be beneficial.

GROUP A-4. Beneficial treatment may be accomplished by stage construction, bituminous application and cushion courses under macadams, and admixtures of cohesive materials to an appreciable depth in the subgrade. In extreme cases the natural soil should be replaced with non-heaving granular material to the lower limit of frost penetration.

TYPE OF SURFACE PERMISSIBLE GROUP A-3 If the soil is treated, a substantial wearing-coarse should be adequate. On untreated soils moderately thick non-rigid or thin rigid pavements are desirable.

GROUP A-4- When natural or artificial drainage is adequate a concrete pavement may be built of medium thickness (not less than 8"-6-8") or a macadam surface may be built either thick or moderately thick depending upon whether the soil is untreated or treated. When the ground-water level is high and drainage is impracticable, macadam is an unsuitable surface; in this case a thick concrete pavement should be used (not less than 9"-7-9"), with crack control and steel reinforcement.

IDENTIFICATION OF THE SOIL IS INDICATED BY THE VALUES SHOWN IN THE FOLLOWING TABULATION:

GROUP	LOWER LIQUID LIMIT	PLASTICITY INDEX	SHRINKAGE LIMIT	MOISTURE EQUIVALENT CENTRIFUGE	MOISTURE EQUIVALENT FIELD
PER CENT	PER CENT	PER CENT	PER CENT	PER CENT	
A-3	10 to 35		NOT SIGNIFICANT	LESS THAN 12	———
A-4	20 to 45	CURVE 3 or LESS	30 or LESS and CURVE 6 or LESS	APPROXIMATELY CURVE 10	EXPANSIVE VARIETY (MICA) HIGHER THAN C.M.E.

VALUES OF CONSTANTS OF THREE TYPICAL GROUP A-3 AND A-4 SOILS WITH RELATION TO MASTER CURVES

GROUP A-3- ○-Fraction of crushed diabase passing 20 and retained on 100-mesh seive. The angularity of the grains produces high internal friction and consequently a higher lower liquid limit.

□-Florida sand-excellent subgrade for relatively-thin flexible surfaces, flows readily when wetted.

△ Minnesota sand-becomes highly stable with bituminous treatment covered with granular blotting layer.

GROUP A-4- ●-A New Hampshire silt that has been observed to suffer detrimental frost heave.

■-A street on this Minnesota silt heaved 3 feet during the winter of 1928-1929.

▲-A Maryland silt containing small amount of mica. Pavements laid on soils of this character in the District of Columbia have cracked before the concrete attained appreciable strength.

FIGURE 19.—Groups A-3 and A-4

SUGGESTED DESIGN ON GROUP A-5 SUBGRADES

CHARACTER OF SOIL.—This soil is similar to that of Group A-4 except that it provides highly-elastic riding surfaces with appreciable rebound upon removal of load, even when dry.

PREPARATION OF SUBGRADE.—These soils require thorough manipulation in order to obtain a uniform density. Compaction with a heavy roller is apt to cause non-uniform rebound of the soil during pavement construction. Drainage must be provided to intercept seepage and reduce the adverse effects of frost heave.

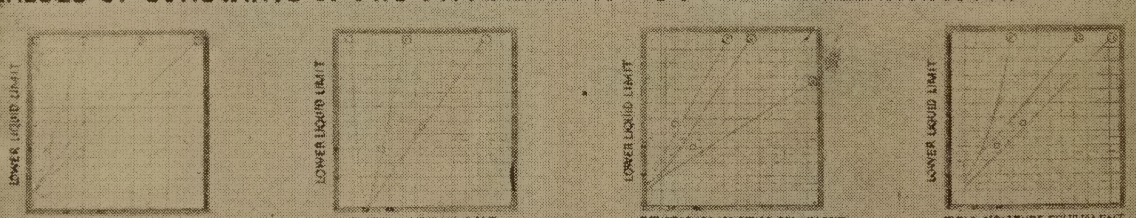
TREATMENT OF SUBGRADE.—Beneficial results may be accomplished by stage construction; bituminous applications and cushion courses are advisable under porous base courses. Clay may may be added with good results when the elasticity of the non-plastic varieties interferes with pavement construction.

TYPES OF SURFACE PERMISSIBLE.—Macadam should be used only after the subgrade has been stabilized by both treatment and drainage. When the ground-water level is high and drainage is impracticable, a thick concrete pavement should be used (not less than 9"-7"-9") with crack control and steel reinforcement.

IDENTIFICATION OF THE SOIL IS INDICATED BY THE VALUES SHOWN IN THE FOLLOWING TABULATION:

Lower Liquid Limit	Plasticity Index	Shrinkage Limit	Moisture Equivalent	
			Centrifuge	Field
PER CENT 20 and Over	Less than Curve (3)	May be as Small as 25 Generally Greater than 30 and Greater than Curve (6)	No Water-Logging	Much Larger than Curve (11)

VALUES OF CONSTANTS OF TWO TYPICAL GROUP A-5 SOILS WITH RELATION TO MASTER CURVES



○-A Penn fine sandy-loam from Virginia that contains 20 per cent of mica.

□-An Oregon silt containing appreciable organic matter. The elastic silts are affected by frost heave far above the ground-water level and are apt to be softened by moisture raised at least 4 feet above the water table by capillarity.

FIGURE 20—Group A–5

SUGGESTED DESIGN ON GROUP A-6 SUBGRADES

CHARACTER OF SOIL.—These subgrades consist of clay soils without coarse material. In the wet compressed state they absorb water only if manipulated. Deformation occurs slowly and there is little rebound upon removal of the load. The soil possesses shrinkage properties. It may be unsatisfactory if used in fills because of excessive volume change. There is not apt to be adverse frost heave unless the soil is in an extremely permeable state.

PREPARATION OF SUBGRADE.—These soils require thorough consolidation in connection with a moderate amount of sprinkling and mechanical manipulation when necessary. Drainage is required to intercept seepage when the soil is in a permeable state (perhaps intersected by cracks and root holes). In fills mechanical manipulation is very beneficial. The fills should be built in the dry season. Coarse material should be added where available. Springs entering from below should be piped away.

TREATMENT OF SUBGRADE.—Beneficial results may be obtained by stage construction, or a bituminous treatment covered with a blotter layer of granular material. Applications of hydrated lime and similar material prior to the bituminous application is apt to increase the depth of penetration of the bitumen.

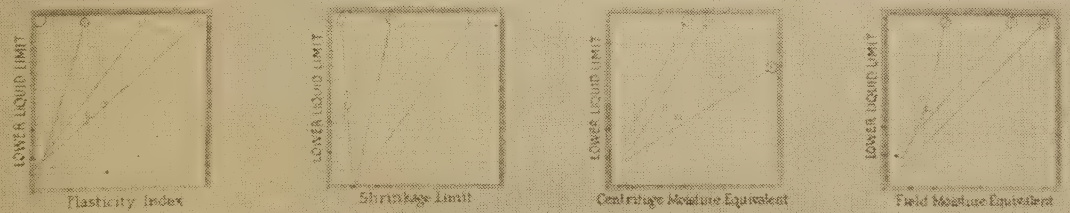
TYPE OF SURFACE PERMISSIBLE.—When the soil is in a homogeneous state and drainage not feasible, ample load distribution should be provided by a thick macadam or a rigid pavement, the required degree of load distribution depends upon the softness of the subgrade. Macadam should be used only after the soil has been surface treated. In rigid pavements crack control is necessary to reduce the adverse effect of non-uniform subgrade shrinkage. When the soil is in the permeable state and drainage is feasible, either macadam or rigid-type surfaces may be used; but when drainage is not feasible there should be used very strong macadam, or a rigid pavement with crack control and steel reinforcement.

IDENTIFICATION OF THE SOIL IS INDICATED BY THE VALUES SHOWN IN THE FOLLOWING MASTER CURVES:

Lower Liquid Limit	Shrinkage Limit	Moisture Content	
		Centrifuge	Field
PER CENT 35 and Over	Curve (5)	Water-Logs Above 40 per cent	Approximately on Curve (11)

GROUP A-6 AND GROUP A-7 SUBGRADES ARE APT TO POSSESS LINEAL SHRINKAGE OF 5 OR GREATER.

CONSTANTS OF TWO TYPICAL GROUP A-6 SOILS WITH RELATION TO MASTER CURVES



○ - A colloidal soil from the bottom of the Potomac River, at Washington, D.C. This soil is unsuitable for hydraulic fills.

□ - A colloidal clay from Missouri that caused trouble by sliding in a cut.

FIGURE 21.—Group A-6

SUGGESTED DESIGN ON GROUP A-7 AND A-8 SUBGRADES

CHARACTER OF SOIL: GROUP A-7.-Similar to Group A-6 except that when moist they are apt to deform quickly when loaded, and rebound similar to Group A-5 subgrades, upon removal of load.

GROUP A-8.-These soils consist of very soft peats or mucks. They are apt to contain capillary moisture in abnormally large amounts far above the ground-water level.

PREPARATION OF SUBGRADE: GROUP A-7 -Mechanical manipulation is required to prevent unequal expansion of the soil. Compaction by a heavy roller may prove to be detrimental. Drainage should be provided to eliminate gravitational water.
GROUP A-8.-A fill of coarser-grained soil should be built across these muck soils which should be consolidated and displaced where necessary by explosives. The capillary moisture-content may be appreciably reduced only when it is practicable to install drains at a considerable depth (10 feet or more)

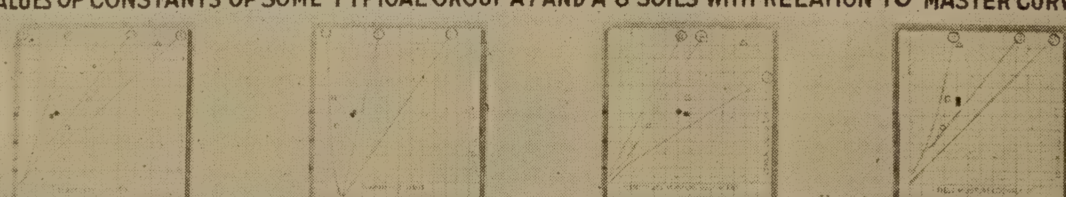
TREATMENT OF SUBGRADE: GROUP A-7-Beneficial results may be accomplished by the stage-constuction method. Expansion beneath freshly-laid concrete pavement may be reduced by bituminous applications or tar paper.
GROUP A-8.-No beneficial treatment yet devised.

TYPE OF SURFACE PERMISSIBLE-GROUP A-7-The proper types of surface are identical only with those shown for Group A-6 subgrades for the condition where the soil is in a homogeneous state and drainage is not feasible.
GROUP A-8.-The pavement requires ample "beam strength", adequate crack control, and steel reinforcement.

IDENTIFICATION of the soil is indicated by the values shown in the following tabulation:

Group	Lower Liquid Limit	Plasticity Index	Shrinkage Limit	Field Moisture Equivalent
	PER CENT			
A-7	35 and Over	Between Curves ③ and ④	Curve ⑤ or Above	Between Curves ⑪ and ⑫
A-8	45 and Over	Less than Curve ③	Approaching Curve ⑥	Greater than Curve ⑪

VALUES OF CONSTANTS OF SOME TYPICAL GROUP A-7 AND A-8 SOILS WITH RELATION TO MASTER CURVES



GROUP A-7-○-An expansive Missouri clay on which a concrete pavement cracked appreciably during the setting period.
□-A gumbo from the Red River Valley in Minnesota. This soil does not suffer detrimental frost heave. It is stabilized when oil treated and covered with a granular blotter-layer.
△-A highly-colloidal soil from Mississippi. This soil affected adversely a concrete pavement laid upon it. This soil should not be used in fills and should be covered in cuts with good material at least 2 feet in thickness.
GROUP A-8:●-A muck from the bottom of the Potomac River at the National Capital, that is considered unfit for hydraulic fills.
■-A Minnesota muck apt to displace laterally under a superimposed fill.

FIGURE 22.—Groups A-7 and A-8

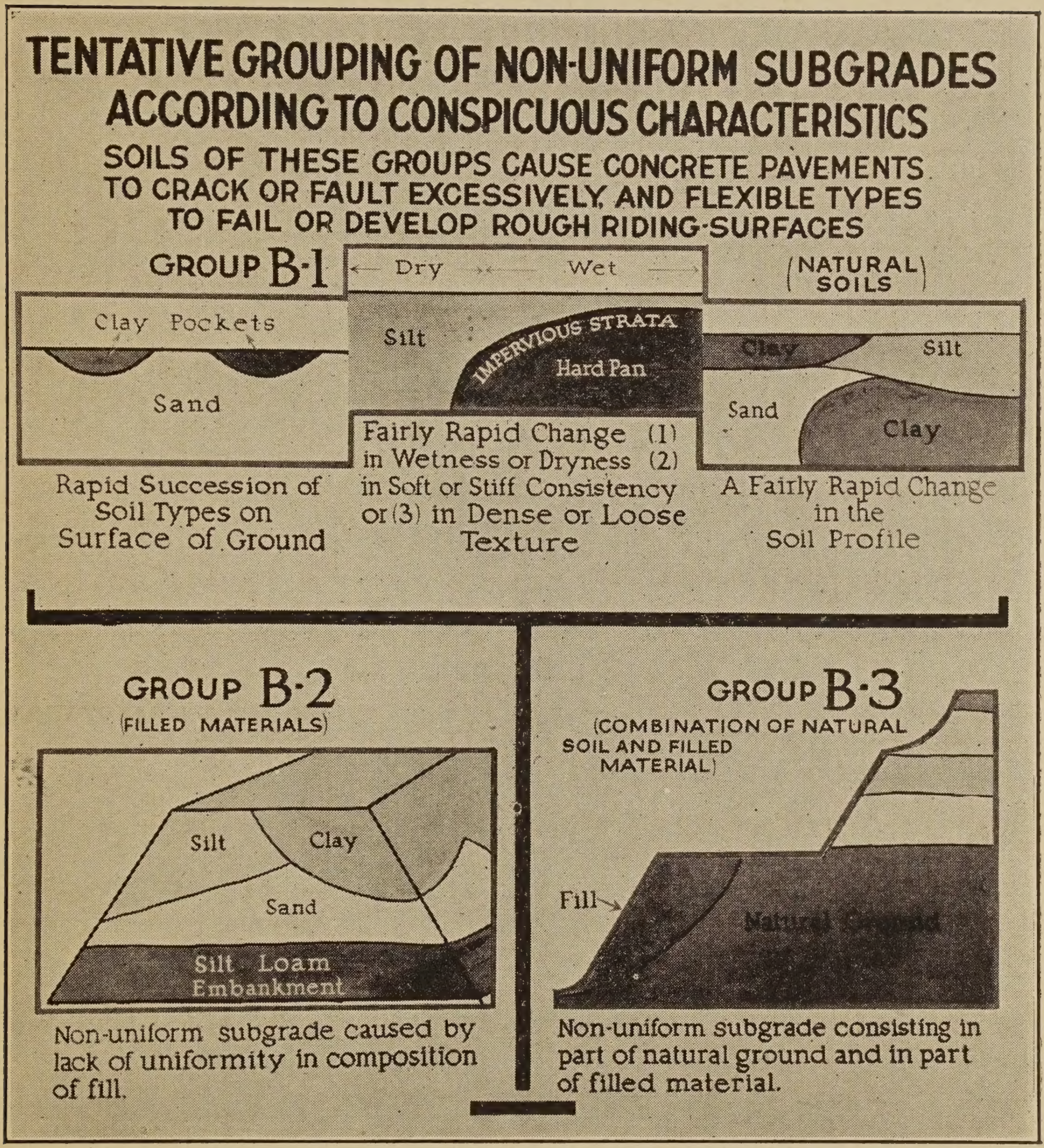


FIGURE 23.—Nonuniform subgrades

SUGGESTED DESIGN FOR GROUP B-1, B-2, AND B-3 SUBGRADES

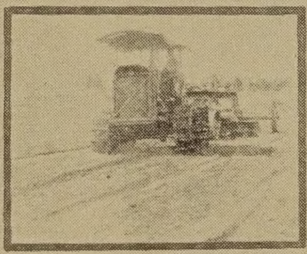
DEFINITE CONCLUSIONS as to these subgrades will not be available until the report, in preparation jointly by the Bureau of Public Roads and the Bureau of Soils of the United States Department of Agriculture is completed. Tentative recommendations, however, may be advanced as follows:

PREPARATION OF SUBGRADE.—

B-1-If non-uniform layer is shallow mechanical manipulation is required to increase the uniformity of the soil. Drainage should be provided at soft spots and to intercept seepage.

B-2-Non-uniform fills should be avoided wherever possible.

B-3-Fills should be compacted as much as possible before placing the pavement. Any springs or water veins, which might enter the fill through the base should be carefully piped away.



TREATMENT OF SUBGRADE.—

B-1-A subbase may be beneficial.

B-2-More uniform compaction by mechanical manipulation recommended.

B-3-No recommendations as yet.

TYPE OF SURFACE PERMISSIBLE.—

B-1-If non-uniform layer is very deep and very non-uniform; a rigid pavement with crack control and steel reinforcement is recommended.

B-2-Rigid pavement with great "beam strength", crack control, and steel reinforcement is recommended.

B-3-Rigid pavement with great "beam strength", crack control, and steel reinforcement is recommended, especially at boundary between excavation and natural-ground surface.

FIGURE 24.—Nonuniform subgrade design

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